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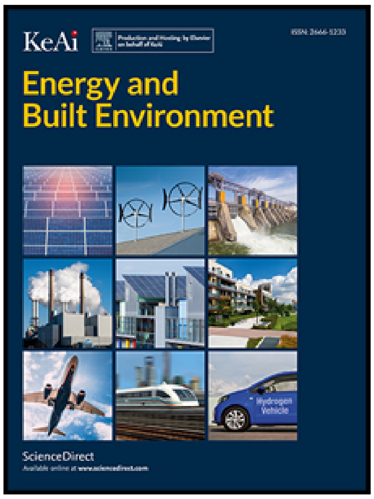

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Highlights

- Dataset obtained from a pneumatic conveying process with electrostatic flow meters
- Solids mass flow rate, particle velocity and air-solids ratio varied for each test
- Machine learning utilised to derive a model for prediction of meter rms voltage
- Model yields accurate meter voltage prediction for wide range of flow conditions
- Enables calibration of accurate gas-solid flow meter with velocity compensation

A low-error calibration function for an electrostatic gas-solid flow meter obtained via machine learning techniques with experimental data

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Abstract

In this paper, modelling and machine learning with experimental data and a novel calibration function for a gas-solid flow sensor fusion are presented. Sensor fusion is the use of software that intelligently combines data from multiple sensors in order to improve overall system performance. This technique can be applied to measurement of mass flow rate of solids in a pipeline with non-intrusive electrostatic techniques. Data fusion from multiple heterogeneous/homogenous sensors can overcome the limitations of an individual sensor and measured variable. It is shown that the output voltage of a ring-shaped electrode is predominantly a function of solids mass flow rate and velocity for a flow of bulk solids in a pipeline, when particle size, properties and ambient conditions remain constant. By incorporating solids flow velocity in a proposed mathematical model (obtained via machine learning), meter output voltage could be predicted with superior accuracy, for wide range of different flow parameters from numerous experiments with a pneumatic conveying system. Transposing the model yields a new calibration function which, when deployed in signal processing software, enables accurate mass flow measurement with velocity compensation. The described method also de-necessitates determination of air solids ratio or solids volumetric concentration, thereby enabling simplification of the overall measurement system whilst yielding higher accuracy than calibration methods from previous studies. Accurate flow measurement facilitates enhanced monitoring and controllability of blast furnaces, power stations, chemical reactors, process plants etc. where there are bulk solids flows in pipelines. Optimisation of such highly materially consumptive and energy intensive processes can yield significant reductions in waste and emissions (CO_2, NOx) and increased efficiencies in global production of energy and materials.

Keywords: sensor fusion, machine learning, electrostatic flow measurement, gas-solid flow, pneumatic conveying, multiple non-linear regression

Nomenclature

A_a	Cross-sectional area of pipe occupied by air [m^2]
A_s	Cross-sectional area of pipe occupied by solids [m^2]
d_p	Particle diameter [μm]
L	Distance between electrodes [m]
M	Mass of solids in hopper [kg]
Q_m	Mass flow rate of solids [kg/hr]
R_{as}	Air-solids ratio [dimensionless]
RH	Relative humidity [%]
T	Time interval for cross correlation function [s]
t	Time [s]
V_{rms}	Root mean square meter voltage [mV]
ϵ	Particle electrical permittivity [F/m]
ρ_a	Density of air [kg/m^3]
ρ_s	Density of solids [kg/m^3]
σ	Solids conductivity [S/m]
τ	Time lag in cross correlation function [s]
τ_o	Transport time for solid particles [s]
v_a	Velocity of air [m/s]
v_p	Particle velocity [m/s]

1. Introduction

Gas-solid flows as pneumatic conveying processes are commonplace in industry. They are utilised in coal-fired power stations, blast furnaces and cement, chemical, pharmaceutical and food production processes as a method to transport bulk solids - being a fuel, reactant or food or pharmaceutical constituent. Often, but not always, the gas phase is air. In order to optimise these processes, reduce waste and emissions or increase operational efficiencies, it is desirable to be able to accurately measure the mass flow of bulk solids, preferably in a non-intrusive manner. Online continuous, accurate and reliable flow measurement is a pre-requisite for effective closed-loop control of a wide range of processes and is often a necessity for optimum plant control in many areas of the process industries.

Traditional coal-fired power stations and blast furnaces offer a good example of the requirement for accurate solids flow measurement in industry. In blast furnaces, pulverised coal (or coke) is also a source of carbon for steel production, as well as a fuel. In both traditional coal-fired power plants and blast furnaces, coal (or coke) is pulverised prior to transport via pneumatic conveying (with air) to the furnace via where it enters via many separate tuyeres (nozzles). An optimum ratio of coal and air is necessary to ensure high combustion efficiency, otherwise incompletely combusted material may end up in the ash. This then presents additional solid waste material disposal burden and is an undesirable squandering of resources. Another parameter which must be accurately measured and subsequently controlled is the velocity of the conveyed fuel. If it is too low, then the flow stream can become stratified and may even cease to flow. This could cause burners to drop out, process temperature to deviate and the formation of obstructions could potentially result in an explosion. If the velocity is too high, then there may be excessive consumption of fuel (and so increased costs), potential for incomplete combustion and heightened levels of abrasion and damage to equipment and pipelines. Over-consumption of fuel also results in additional and unnecessary emissions of CO_2.

Failure to measure and effectively control both mass flow rate and velocity can also result in the excessive formation and emission of nitrogen oxides (NOx) which cause ozone depletion and environmental acidification. As well as this, issues with the excessive deposition of molten ash and incombustible by-products, known as slagging, can occur inside the furnace, reducing the overall efficiency of the plant. To minimise the potential for aforementioned issues and to minimise oscillatory process response, inconsistent/uneven flame magnitude and unintentional drop-out of individual burners, the mass flow rate and velocity of fuel to each individual tuyere must be controlled so as to be equivalent and consistent. The input gas-solid flow as an air-fuel mixture is transferred to the furnace through many (often more than a dozen) tuyeres via separate conveying pipelines downstream of a distributor, i.e. the flow is split into different streams. Accurately maintaining an equal and consistent supply to each burner necessitates closed-loop control, and therefore measurement of, the fuel flow rate through each individual conveying line. Optimum burner control and furnace operation therefore necessitates a non-intrusive gas-solid flow measurement system like the one described in this paper.

Increasingly, newly built modern coal-fired power plants instead employ dense phase conveying, whereas the system described in this paper is more suitable for lean phase conveying, so will be more applicable to older less-efficient plants, as a means of reducing waste, emissions (CO2, NOx), process deviations etc. and therefore resulting financial implications and overall operating costs. A similar type of metering system would also be applicable to other industrial processes where a flow of pneumatically conveyed bulk solid material, fuel or reactant is required to be distributed to downstream reactors, furnaces or other vessels. Flows within large scale pneumatic conveying systems used to transport chemicals or other bulk solids (e.g. powders, pelletised fuels/materials) from one area of a process plant to another could be effectively monitored and controlled, improving operability and reliability. A range of industrial processes, in the production of chemicals, materials, pharmaceutical and food products, could be significantly optimised through the provision of accurate non-intrusive gas-solid flow metering technology, this being the underlying incentive for continuing research and development in this area.

There are various meters that are already commercially available that do enable measurement (or at least detection) of flow of bulk solids [1], some of which are intrusive in nature, and are unable to conduct measurement without disturbing the flow stream. This is undesirable and wastes energy which has been already invested in the transfer of material. Also, some designs may be damaged over time by constant abrasion due to the high level of kinetic energy possessed by the fast-flowing solids. As such, invasive (e.g. various probes) and semi-obstructive (e.g. Coriolis) measurement systems are usually deemed unsuitable for continuous service on two-phase gas-solid pneumatic conveying pipelines and non-intrusive meter designs are preferable, though there is a need for such systems to offer greater accuracy.

There are many different non-intrusive gas-solid flow measurement system designs presented in the literature. Many authors present methods based on attenuation, scattering and Doppler techniques using optical sensors [2], digital imaging techniques [3], microwaves [4] x-rays and gamma rays [5] and ultrasonic waves [6] to measure both solids volumetric concentration and flow velocity. A main issue with optical techniques is that a sensing window is usually required, which can then become contaminated resulting in the detection of false signals leading to errors. The same is true for systems which employ digital image processing techniques which is unfortunate given that one study combining a digital imaging approach to concentration measurement with electrostatic velocimetry [3] purported solids mass flow rate measurement with a maximum error of around ±4%. This level of accuracy is commendable (for a multiphase meter), however the described system would be inapplicable in many industrial scenarios, with bulk materials which result in contamination and also with denser solid phase flows.

In a studies employing ultrasonic methods [6], the solids concentration can be inferred from attenuation and the gas phase velocity can be determined from the acoustic propagation velocity. However, the solids velocity is estimated using an assumed value for slip velocity (between gas and solid phase), which can vary. Therefore, there is some uncertainty in the solids velocity and the mass flow rate which is derived from combining the former with the measured concentration. Optimum frequency is dependent on the size of the particles, and multiple transducers may be required if the cross section of the pipeline is relatively large. Yan states the difficulty of using acoustic methods [7] due to high attenuation in gases and high particle impingement noise.

Radiometric systems based on microwaves, x-rays and γ rays have also been designed to enable velocity, concentration and mass flow rate measurement though those with divergent interrogation beams incur spatial sensitivity error across the pipe cross section. Designs with many narrow parallel γ ray beams [5] perform better, though such designs are expensive due to their inherent complexity, also use of ionising radiation is usually avoided in commercial or industrial applications unless completely necessary. Magnetic resonance imaging is another non-invasive technique found in the literature [8] but again it is costly due to complex construction. Also, it requires the pipe section to be made from a material which does not attenuate electromagnetic fields and so cannot be effectively grounded. Also, as Kawaguchi [8] states, the time resolution is poor, which limits the maximum flow rate which can be measured.

Numerous studies have been conducted with electrical sensing methods [9-20], such as the one presented in this paper. Many commercially available non-intrusive meters based on electrostatic techniques have been deployed in power stations [9] and blast furnaces, though whilst they can offer flow detection, they currently lack the accuracy to be utilised in furnace/reactor control loops, which limits the potential for process optimisation. The main limitations of these types of sensor are that they are particularly sensitive to factors such as humidity and/or moisture content, particle size and (electro)chemical properties of the bulk solid material itself. Another drawback is non-uniform spatial sensitivity as analysed by Zhang [10], with an adverse effect on the sensors output being more pronounced for non-dispersed, heterogeneous or roping flow regimes. Also, the induced voltage is dependent on a wide range of different parameters, rendering it somewhat challenging to extract useful information from the raw signal. Capacitive tomography techniques have been deployed [11] to visualise flow pattern and can be combined with electrostatic tomography [12] in order to improve performance, though there is a trade-off between resolution (or number of pixels) and sensitivity, as for an increased number of individual electrodes they must therefore be smaller in width in order to fit around a given pipe circumference. However, all of previously described sensing methods are more complex and costly than electrical sensing methods and, as shown in the following sections, it is possible to overcome these limitations and attain reasonably accurate values for solids flow velocity and mass flow rate using simple electrodes.

A well-studied non-intrusive electrostatic solids flow sensor design, often deployed under lean phase conditions, is the ring-shaped electrode. Many decades of research [13] detail the development of gas-solid flow measurement systems utilising sensors of this type, though as attaining high accuracy presents a significant measurement challenge, the field of research continues to be active. In order to maximise potential performance, it is necessary to model this type of sensor, and research usually adopts one of several approaches. The first is modelling of dynamic characteristics of the sensor with regards to flow characteristics, particle distribution and size [14]. Another area of focus is on modifying the sensor structure, e.g. electrode width [15] in order to analyse performance. Zhang presents a means to improve spatial sensitivity through reweighting of the signal spectrum [16]. Many publications relate to measurement of flow velocity via the cross-correlation technique [17-20]. Another avenue is modelling of the sensor in order to predict its output [21] with regards to flow rate, concentration etc. with consideration of effects of various parameters including velocity, with some studies utilising measured velocity to compensate its apparent effect on the measured voltage,[20] as a way to improve measurement accuracy.

The focus of this paper is more relatable to the latter, though presents findings in the form of a novel calibration function and models exhibiting a higher level of accuracy to those previously described [20-21], with a reduction in design complexity by de-necessitating determination of air-solids ratio or solids volumetric concentration. The described approach differs to other methods in the literature which often deploy complex apparatus [2-8] for measurement of solids volumetric concentration (e.g. via tomography, radiation/absorption, digital imaging techniques) in addition to velocity measurement (often via cross-correlation [22]), combining both of which to obtain an indirect measurement value for mass flow rate. With the methods and calibration function presented in this paper, only two or more ring-shaped electrodes and effective signal processing are required to determine mass flow rate to a good degree of accuracy. Given that in industrial scenarios there are often many separate distributed conveying lines feeding furnaces, reactors or vessels such that many meters may be required, it is desirable for the design to be of relatively low cost/complexity, require minimal maintenance, yet offer good performance.

As shown in Figure 1, the ring-shaped electrode is installed flush with, though electrically insulated from the pipe wall. The pipeline either side of the sensor assembly should be earthed, to avoid high levels of electrostatic charge accumulation, brush/corona discharge and the potential for explosions should the minimum energy be exceeded. The design is relatively simple and therefore low cost.

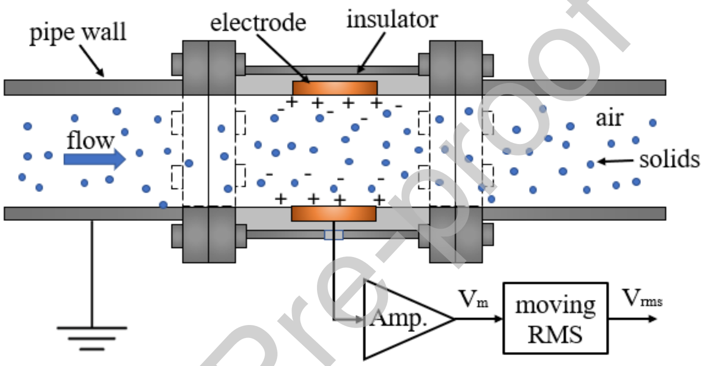


FIG. 1 - Diagram of electrostatic ring-shaped flowmeter

This arrangement does not impede the flow of solid particles in the conveying line and so minimises electrode wear, though allows the electrode to be sensitive to the electrostatic charge carried by the flowing solids. The charge is generated through contact electrification or the triboelectric effect as the particles collide with each other and the pipe wall. For lean phase conditions, with an increase in mass flow rate, one can usually expect a higher output voltage from the meter. Unfortunately, the relationship is not one of direct proportionality or even non-linear one. There are many other variables which affect the measured voltage which must be considered.

2. Modelling

A main issue is that, unlike simpler measurement systems, the voltage induced in the electrode is related to not only the mass flow rate of solids, but also air-solids ratio, particle velocity, flow profile, particle size [13], humidity, air density and the electrostatic properties of the bulk material itself. It is a complex relationship with many interacting variables resulting in the measured voltage signal. The raw signal is noisy AC, so the rms (root mean square) voltage is utilised, which is the quadratic mean and a measure of the energy content of the signal. When assuming a dispersed/homogenous flow

(1)

regime within a given pipeline, a comprehensive model of the electrostatic ring-shaped flow meter which yields output (rms) voltage would be a complex function of multiple constituent variables.

$$V_{rms} \cong f(Q_m, R_{as}, \mathrm{v}_p, d_{p,} RH, \rho_a a\, \sigma, \epsilon)$$

However, one can assume that some of the latter variables remain sufficiently constant for a given system. Variables and conditions can be controlled/fixed under experimental (or industrial process) conditions and from subsequent observation it was found for a conveying system using the same bulk solid material, same grade or particle size, humidity and ambient conditions, the output (rms) voltage of a ring-shaped electrode around a conveying pipeline can said to be predominantly a function of the mass flow rate Q_m, air-solids ratio R_{as} and particle velocity v_p. The meter function to be found is therefore;

$$V_{rms} \cong f(Q_m, R_{as}, \mathrm{v}_p) \tag{2}$$

A model for the calibration of an electrostatic flow sensor of this type has been presented previously by Zhang [21]. This model expressed meter output voltage as a function of air-solids ratio and mass-flow rate, but did not incorporate particle velocity, or at least not as a distinct variable, and was of the form;

$$V_{rms} = (AR_{as} + B)\, Q_m^2 + (CR_{as} + D)Q_m + ER_{as} + F \tag{3}$$

Where A, B, C, D, E and F are constants to be determined. This model was found to have a maximum relative error of around 7%. Whilst this level of error would likely be considered too high for a single-phase meter, for a multiphase meter it is actually acceptable, though a greater level of accuracy is desirable. Also, if possible, it would be beneficial to have a model which does not require air solids ratio, as it is challenging to measure practically, requiring additional hardware and signal processing. Therefore, the aim of this research is to obtain a new system model for an electrostatic gas-solid flow meter which exhibits superior relative accuracy, incorporates particle velocity, and de-necessitates determination of air-solids ratio. This will then lay the foundation for a gas-solids flow metering system of relatively low complexity yet a useful degree of accuracy, sufficient for industrial application.

As solids mass flow rate has proven difficult to measure directly, this measurement challenge is still of research interest in a time when single phase gas and liquid flow meters (e.g. Coriolis) exist with stated accuracies of 0.05%. Current multiphase gas-solid flow meter designs are somewhat behind, usually no better than ±10%, but it is thought that accuracy can be improved by utilisation of multiple homogenous or heterogeneous sensors and combining data in software to improve system performance in a method termed ‘sensor fusion’. With electrostatic gas-solid flow measurement, this can be achieved through the use of multiple ring-shaped electrodes at different positions on the pipeline. This can reduce the issue of sensitivity to flow profile and enable simultaneous determination of particle velocity using the cross-correlation technique [22], which is a well-understood technique described and demonstrated in the literature [17-19]. If an upstream voltage signal from the flow of electrostatically charged solids is denoted as x(t), and a delayed signal at a downstream position is y(t), then the transport time τ_0 can be found via the cross correlation function $R_{xy}(\tau)$ of x(t) and y(t), for the time interval T which is defined by;

$$R_{xy}(\tau) = \lim_{T\to\infty} \frac{1}{T}\int_0^T x(t)y(t+\tau)dt$$

Where $R_{xy}(\tau)$ is maximum when $\tau = \tau_0$. Although the delayed downstream version of the signal may differ somewhat, this technique is still very effective. As the distance L between the electrodes is known, the charged particle velocity can be calculated as;

$$\mathrm{v}_p = \frac{L}{\tau_0} \tag{5}$$

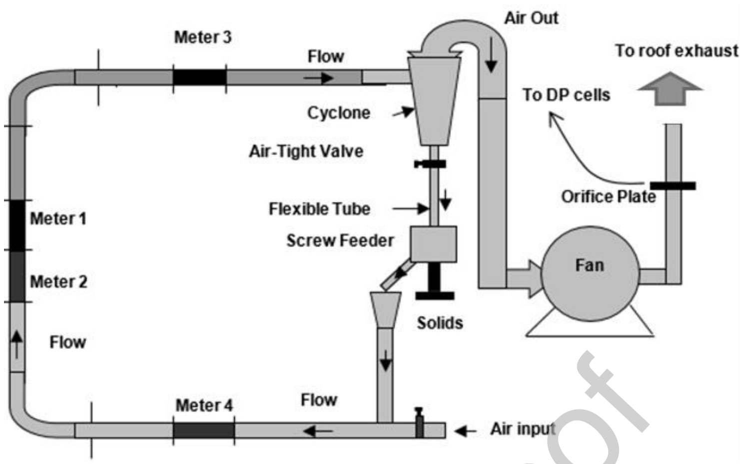
In several studies [17-18] regarding electrostatic gas-solid flow measurement, the flow or particle velocity is the intended measurand, acquisition of which often being the main scope/objective of the research. In other studies [20], the measured velocity is used to compensate the measured voltage signal, to increase the accuracy of mass flow measurement. One such technique, which has actually been deployed in some commercial metering systems, is to divide the measure rms voltage by the velocity times a constant k_G;

$$Q_m = \frac{V_{rms}}{k_G v_p} \tag{6}$$

However, it is thought that an improved model and calibration function can yield greater accuracy, the acquisition of which being the underlying aim of this research. To obtain such a model, and to discern its accuracy, experimental data must be first acquired from a pneumatic conveying system.

3. Obtaining Experimental Data

The Teesside University pneumatic conveying rig shown in Figure 2 was used to collect data. A 40mm pipeline containing conveyed solids consists of a vertical and horizontal section with 4 electrostatic meters. The configuration enables simultaneous measurement of particle velocity using the cross-correlation technique. An inverter-controlled fan takes in air, which is mixed with solids

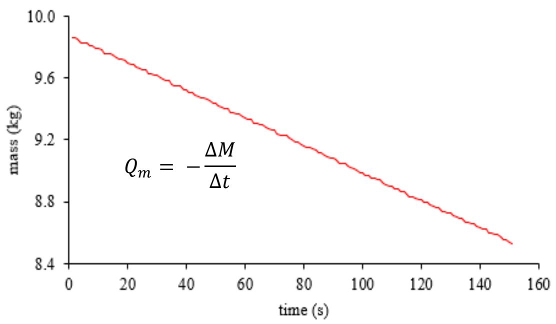


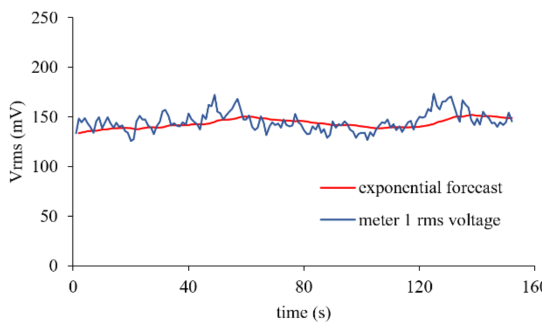
(Fillite – extracted from power station fly ash) and introduced to conveying line via a screw feeder. The mass of solids in a supply hopper is con[illegible]sly weighed using a load cell, and the reference solids mass flow rate is obtained by mass differentiation with respect to time. An additional inverter controls the speed of the screw feeder. Air flow rate is measured downstream and air exits the system via an exhaust.

FIG. 2 – Diagram of pneumatic conveying system

FIG 3a – Mass flow rate reference **FIG. 3b** – Meter 1 rms voltage

The instantaneous root-mean square voltage from each meter, the mass of solids in the hopper, the air flow rate and solids velocity are all logged in software (Labview) every second during an experiment. Twenty five different experiments were conducted, all with different mass-flow rates, solids velocity and air-solids ratio. Over 5000 data samples of each parameter were obtained. These values were then used to form a split train/test data-set, to enable acquisition of system model via machine learning techniques. As an example, Figures 3a and 3b show data for solids mass (kg) in the hopper, used to





obtain a reference value for mass flow rate (kg/s) and meter 1 output rms voltage (mV) respectively during one such experiment, for a mass flow rate of approximately 33.5 kg/hr and average velocity of around 37 m/s. The directly measured parameters and their respective measurement accuracies are listed below. Other parameters, e.g. mass flow rate, air solids ratio, are then inferred from these measurements.

- Meter voltage (mV) ±0.01%
- Mass of solids (kg) ±1%
- Particle velocity (m/s) ±2%
- Air velocity (m/s) +2.5%

4. Preliminary Model Derivation with Machine Learning

Using the Regression Learner app in MATLAB, a variety of machine learning algorithms were deployed with the train data set (70% of overall data) and are ranked below in Table 1 order of their respective model performance metrics; R^2 value, root mean square error (RMSE) and mean absolute error (MAE).

Table 1 Machine learning techniques with model performance metrics (ranked)

Method	R^2	RMSE (mV)	MAE (mV)
Linear Regression	0.93	11.37	9.07
Linear State Vector Machine	0.93	11.48	9.10
Boosted Regression Tree Ensemble	0.89	14.69	10.86
Fine Regression Tree	0.87	15.86	12.46
Bagged Regression Tree Ensemble	0.84	17.30	13.15
Fine Gaussian State Vector Machine	0.74	22.39	15.00

As can be seen, the best-fitting model/technique of those tried is linear regression. This enables the derivation of a linear equation for meter output voltage;

$$V_{rms}(mV) \cong 3.3Q_m + 2.1\mathrm{v}_p + 8.3R_{as} - 48.2 \quad (7)$$

As well as having the best fit to test data, with this type of model there is less concern with regards to overfitting a because the data conforms well to a simple model rather than requiring say a complex regression tree, or state vector machine. Yan [23] utilised machine learning with artificial neural networks to be able to attain accuracy of around ±15% with the same type of meter. However, a greater level accuracy is desirable and also with ANN techniques is difficult to interpret the model structure whereas with a mathematical model in the form of an equation it is easier to do so. The data used to train the linear regression model were all instantaneous values, and so show some variance from the mean. Although this will inevitably affect the initial fit of the model, the fit will be improved with regards to steady-state (moving) averaged data. However, a higher order model, accurate within the specified range, that captures the non-linear nature of V_{rms} with Q_m and yields zero output for zero flow is desired.

5. Model Enhancement

An improved model should also encapsulate the slightly non-linear/curved nature of meter voltage with increased mass flow rate. This is seen in the data set when experiments with similar flows parameters are grouped in terms of air solids ratio and velocity to see the effect of altering each parameter and also mass flow rate in isolation. A higher order model which predicts zero output for zero flow is preferable, as it corresponds to the reality of the system intended to be modelled (when disregarding noise). Although the initial linear regression model was deemed insufficient, it facilitates the derivation of the unknown coefficients for a second order polynomial model. A model with a similar structure was presented by Zhang [21] given by equation 3. This model was found to have a maximum relative error of around 7%. The newly proposed model has zero offset, incorporates particle velocity and has the form;

$$V_{rms}(mV) \cong \left(a + bR_{as} + c\text{v}_p\right)Q_m^2 + \left(d + eR_{as} + f\text{v}_p\right)Q_m \tag{8}$$

Where a, b, c, d, e and f are constants/coefficients which can be determined via multiple polynomial regression. Alternatively, they can be obtained through utilisation of the initial multiple linear regression model of equation 7. By substituting values for R_{as} and v_p and then applying the quadratic regression algorithm, a set of n (in this case nine) second order polynomials expressing V_{rms} as a function of Q_m could be obtained as shown in Figure 4. As previously mentioned, there will be no offset term, unlike the model of equation 3. In MATLAB, this constraint can be set when conducting polynomial regression using the following MATLAB function;

```
Pn = polyfix(Qm,Vrms,0,0)
```
(9)

Where Pn is the resulting polynomial function, and the two zeros correspond to the co-ordinates (Q_m, V_{rms}) at the origin. Therefore, the eventual model will yield zero output voltage for zero flow and with zero offset, the set of obtained polynomial functions shown in Figure 4 have the form;

$$V_{rms} = A_n Q_m^2 + B_n Q_m \tag{10}$$

Though the numerical values for the co-efficients A_n and B_n are different for each polynomial, they can be expressed as linear sub-functions of R_{as} and v_p. Obtaining these linear functions will yield an overall model which will express V_{rms} as a function of Q_m, R_{as} and v_p for the domain shown in Figure 4, within which the measured values obtained from experiment reside. For each polynomial in Figure 4 the corresponding values for R_{as} and v_p were substituted and therefore known, as were the coefficients A_n and B_n and found to change incrementally with R_{as} and v_p As for given sets of three of the nine polynomials, one of the parameters R_{as} or v_p was fixed, the constants *a*, *b*, *c*, *d*, *e* and *f* for the overall polynomial model could be determined by means of simultaneous equations;

$$A_n = a + bR_{as} + cv_p \tag{11}$$

(12)

$$B_n = d + eR_{as} + fv_p$$

The constants or coefficients for the proposed model of equation 8 were then determined as;

$$a = 0.047,\ b = -0.008,\ c = -\ 0.002,\ d = 0.111,\ e = 0.546,\ f = 0.136$$

As shown in the following section, this refined non-linear model was subsequently found to be more accurate at predicting meter output voltage than the linear model and significantly more accurate than the model of equation 3 within the range shown. However, it should be noted that if various factors such as the bulk solid material itself, its electrostatic properties, particle size, ambient conditions, electrode dimensions, pipeline dimeter etc. are altered, then the co-efficients will need to be re-determined i.e. these constant values are specific to Fillite flowing in a 40mm pipeline, using the described meter design and for the specified range of mass flow rate 10-40 kg/hr, velocity 15-30 m/s and air-solid ratio 1.5-3.5. In this range equation 8 is valid, though for more expansive ranges a higher order model may be required.

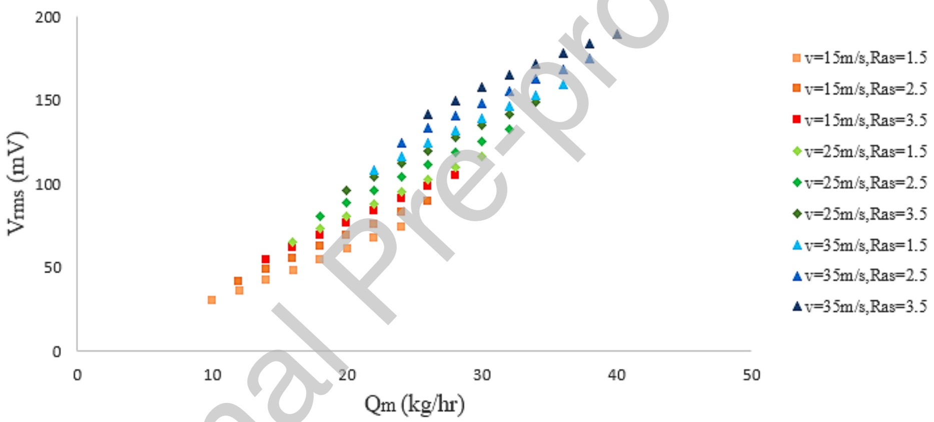


FIG. 4 – Multiple polynomial regression model

Although it should be noted that Figure 4 is formulated via substitution of values into a derived mathematical model, and that practically it may not be possible to alter mass flow rate without altering either particle velocity or air solids ratio, the figure facilitates analysis of the effect of each variable in isolation. As expected, the rms voltage V_{rms} does indeed increase with mass flow rate Q_m, though is clear that both air solids ratio and particle velocity have a modifying effect. Particle velocity seemingly has a greater effect on the output voltage than air solids ratio; modifying the former has a much more pronounced effect on the output rms voltage as modifying the latter by the same proportion. This finding is in agreement with earlier studies [15, 21], including those in which there is an attempt to compensate the effect of velocity [20]. An explanation may be that particles with greater velocity experience a greater number of collisions resulting in a greater transfer and accumulation of electrostatic charge, and so a higher measured output rms voltage is observed. This observation, and those of previous studies, therefore suggest that incorporation of particle velocity in the proposed model is indeed warranted, as it is clearly a dominant variable with regards to its effect on the measured output rms voltage.

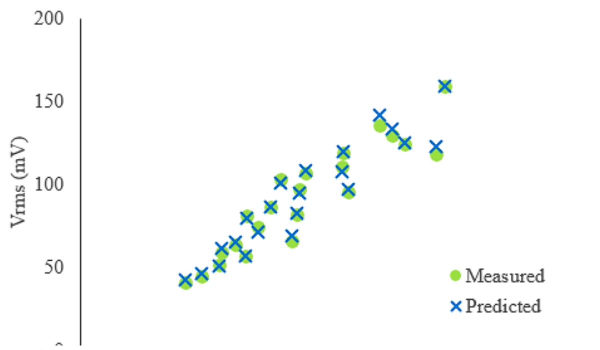
A more challenging observation to explain is that meter output voltage appears to increase with air-solids ratio, i.e. a lower proportion of solids in relation to air. This also agrees with the findings of other studies and Zhang [15, 21] suggests that this is again due to velocity, as for a given mass flow rate, for a higher air solids ratio the velocity is invariably higher if a given mass of solids is to be conveyed per unit time. If this explanation is correct, then it may be possible to eliminate air-solids ratio from the meter model and transposed calibration function yet still maintain accuracy, as the meter output signal appears to be more sensitive to velocity than any other variable, followed by mass flow rate as the intended measurand. If this is possible then the calibration function and the required measurement system can be simplified significantly, de-necessitating determination of air-solids ratio and so requiring just 2 or more voltage signals and the delay between them in order to accurately determine solids mass flow rate. The model of equation 8 is used to predict meter output voltage for a range of flow parameters and compared to experimental data in the following section. In a subsequent section, a refined model which does not incorporate air-solids ratio is then derived and again compared to steady state moving averaged data obtained from twenty five experiments with different flow parameters.

6. Initial Modelling Results

The following table shows the root mean square meter voltage V_{rms} for 25 experiments conducted, using the apparatus of Figure 2 with varying parameters; particle velocity v_p ranging from 15 to 30 m/s, air-solids ratio ranging from 1.5 to 3.5 (which is typical of power station concentrations) and mass flow rate ranging from 10 to 40 kg/hr. The meter voltage is predicted as V_{fcn} using the aforementioned non-linear regression model of equation 8 and the relative error (%) of the prediction is also calculated. The model fit to steady state data from 25 experiments of Table 2 is then shown graphically in Figures 5 and 6.

Table 2 – Experimental data and model

v_p	R_{as}	Q_m	V_{rms}	V_{fcn}	e_r%
15.59	3.29	10.96	41.18	42.85	-4.06
15.56	2.83	12.64	45.47	46.64	-2.57
15.53	2.46	14.51	51.68	50.95	1.40
19.41	3.15	14.72	59.26	62.09	-4.79
19.38	2.84	16.18	63.91	65.77	-2.91
15.46	2.05	17.34	57.59	57.67	-0.14
23.14	3.27	17.40	81.65	80.06	1.95
19.27	2.46	18.57	74.50	71.84	3.57



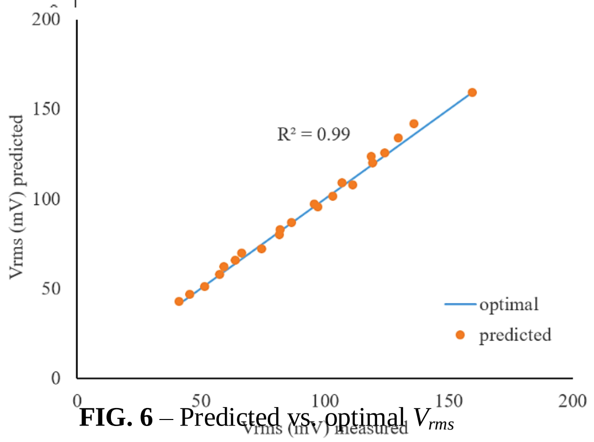


FIG. 6 – Predicted vs. optimal V_{rms}

23.07	2.85	19.86	86.66	86.75	-0.11
26.73	3.23	20.98	103.4	101.3	1.96
15.31	1.58	22.17	66.40	69.59	-4.81
19.23	2.00	22.67	82.02	82.74	-0.88
23.07	2.45	22.99	97.24	95.51	1.78
26.69	2.86	23.56	107.0	108.6	-1.53
22.95	2.03	27.46	111.2	107.8	3.06
26.69	2.43	27.56	119.3	120.0	-0.59
19.01	1.60	28.03	95.79	97.10	-1.37
30.00	2.48	31.43	136.0	141.8	-4.27
26.34	2.03	32.76	129.8	133.7	-3.04
22.50	1.62	34.04	124.3	125.3	-0.80
18.77	1.19	37.29	118.8	123.4	-3.90
29.78	2.03	38.17	159.5	159.1	0.21

It is clear to see from Figure 5 that meter output voltage is not simply directly proportional to solids mass flow rate, and that is due to multiple different parameters, yet the presented model of equation 8 is able to accurately predict meter output voltage from the available data. As expected, the refined model shows an improved fit to steady state (moving) averaged meter voltage, as opposed to instantaneous values from the original sampled data. As can be seen, the maximum relative error is less than 5%. This is more than acceptable for a multiphase flow meter and is constitutes a significant improvement to that of the previous model (eq. 3) from the literature, which did not incorporate particle velocity. However, it is desirable to simplify the model where possible and ascertain whether accuracy can be maintained using less predictor variables i.e. without air-solids ratio, which is more difficult to determine than the other variables, as it does not simply depend on measuring a voltage or the time delay between signals.

7. Model Refinement and Results

As in practice it is difficult to measure air-solids ratio, it is desirable to eliminate it from the model if possible. With the experimental apparatus of Figure 2, it was possible to infer R_{as} via air flow and mass measurements, though in industrial applications with distributed downstream conveying lines this may be difficult or even impossible. If a suitable model can be found where R_{as} is not a predictor variable, no additional instrumentation would be required. A system utilising only ring-shaped electrodes would then be sufficient to measure mass flow rate, as only meter rms voltage and particle velocity would be required to attain it. As both mass flow rate and velocity are both flow variables relating to air solid ratio, it is thought that a model incorporating only V_{rms}, Q_m and v_p can exhibit sufficient accuracy to constitute a useful multiphase meter. The meter function to be found is therefore;

$$V_{rms} \cong \mathrm{f}(Q_m, \mathrm{v}_p) \tag{13}$$

One way to obtain a model of this form is by utilising the previously presented model of equation 8, and the fact that air solids ratio R_{as} may be expressed as;

$$R_{as} = \frac{v_a A_a \rho_a}{v_p A_s \rho_s} \tag{14}$$

As can be seen, R_{as} is itself a function of particle velocity. So, if the density of air, density of solids and occupied cross-sectional area of the pipe remains fairly constant (homogenous flow) coupled with the fact that for each experiment it was found that the ratio of air velocity to particle velocity was also observed to fairly constant, a model of following form can be proposed;

$$V_{rms} = (\alpha + \beta v_p)\, Q_m^2 + (\gamma + \delta v_p) Q_m \tag{15}$$

Using the same method(s) as described in the foregoing section(s), the constants and coefficients of equation 15 have been determined to two significant figures as;

$$\alpha = -2.2 \times 10^{-3}, \quad \beta = -1.0 \times 10^{-3}, \qquad \gamma = 1.8 \times 10^{-1}, \qquad \delta = 1.2$$

Transposing the above model yields a calibration function, implementable in system software, enabling determination of mass flow rate from online measurement of rms voltage(s) and particle velocity;

$$Q_m = \frac{\sqrt{V_{rms}(\alpha + \beta v_p) + 0.25(\gamma + \delta v_p)^2} - 0.5(\gamma + \delta v_p)}{(\alpha + \beta v_p)} \tag{16}$$

The obtained model of equation 15 bears some similarity to those presented in previous work on gas-solid flow metering with velocity compensation [20]. The model of equation 6 intends to compensate the effect of velocity by dividing the measured voltage V_{rms} by measured velocity v_p and a calibration constant k_G. Given in the meter model form expressing expected meter output rms voltage as the subject;

$$V_{rms} = k_G v_p Q_m \tag{17}$$

Which, like equation 15, expresses V_{rms} as a function of v_p and Q_m. In a further study [20], the relationship between meter rms voltage V_{rms}, mass flow rate Q_m and flow velocity v_p was perceived to be;

$$V_{rms} = k_1 v_p Q_m (1 - k_2 Q_m) \tag{18}$$

As can be seen, this is similar to the newly obtained model of equation 15, in that it is second order with regards to mass flow rate Q_m, however it only incorporates two constants k_1 and k_2, whereas equation 15 incorporates four constants, α, β, γ and δ. The two aforementioned velocity compensation functions from the literature were utilised with the (steady state) data obtained from experimentation as detailed in section 3. Optimum values for the constants were found so as to minimise the error of prediction of meter voltage for the given range of mass flow rate and velocity. The performance of the models of equations 17 and 18 are compared with the newly obtained meter model of equation 15 in terms of accuracy of meter output voltage prediction in Figures 7, 8 and 9 respectively.

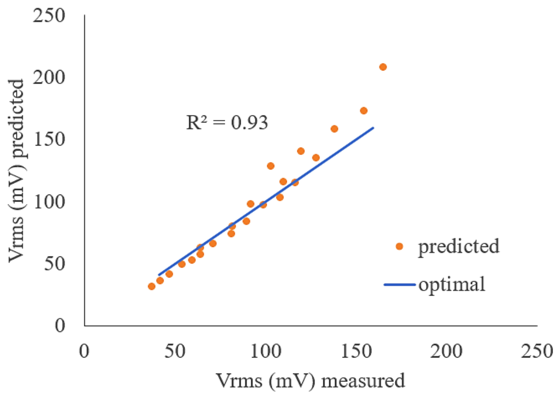


FIG. 7a - Earlier model (eq. 17) fit to V_{rms}

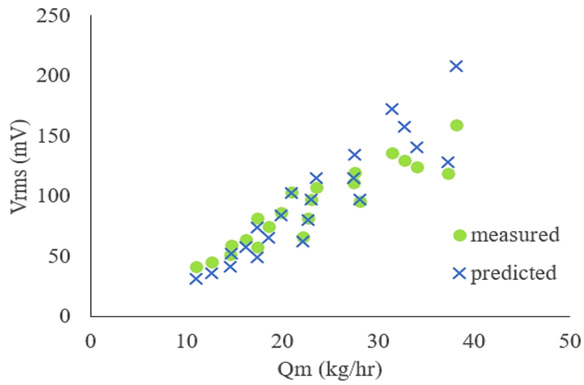


FIG. 7b - Earlier model (eq. 17) fit with Qm

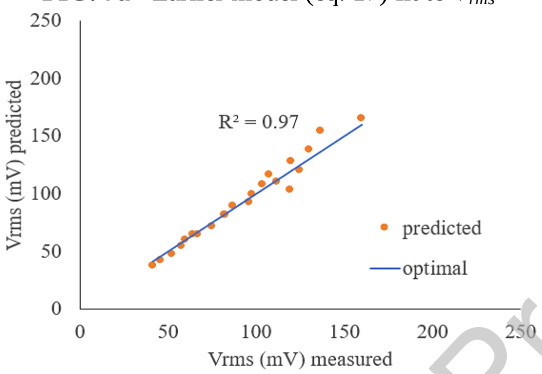


FIG. 8a - Earlier model (eq. 18) fit to V_{rms}

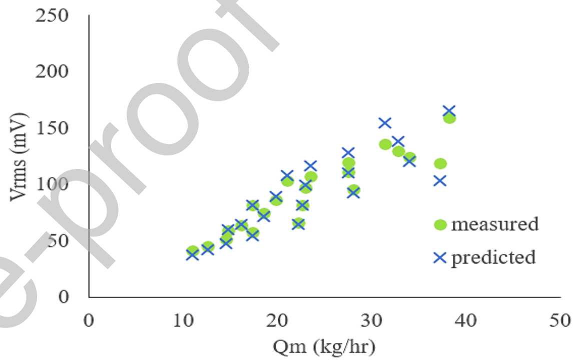


FIG. 8b - Earlier model (eq. 18) fit with Q_m

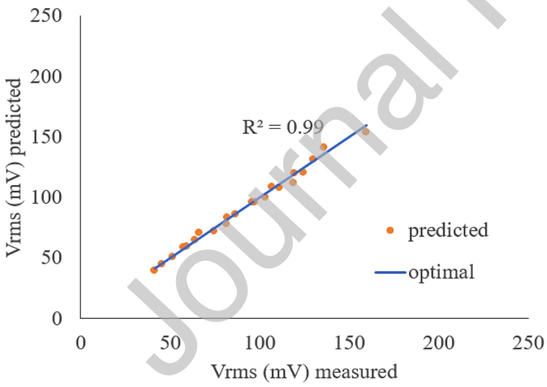


FIG. 9a - New model (eq. 15) fit to V_{rms}

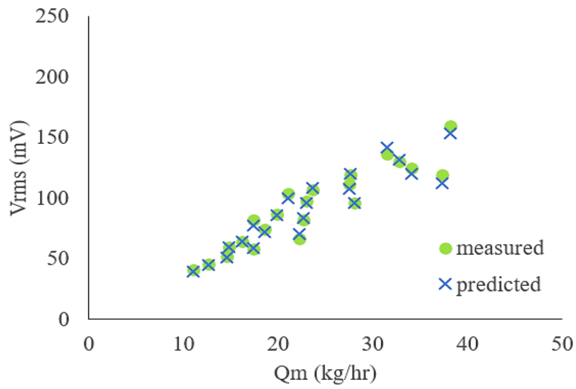
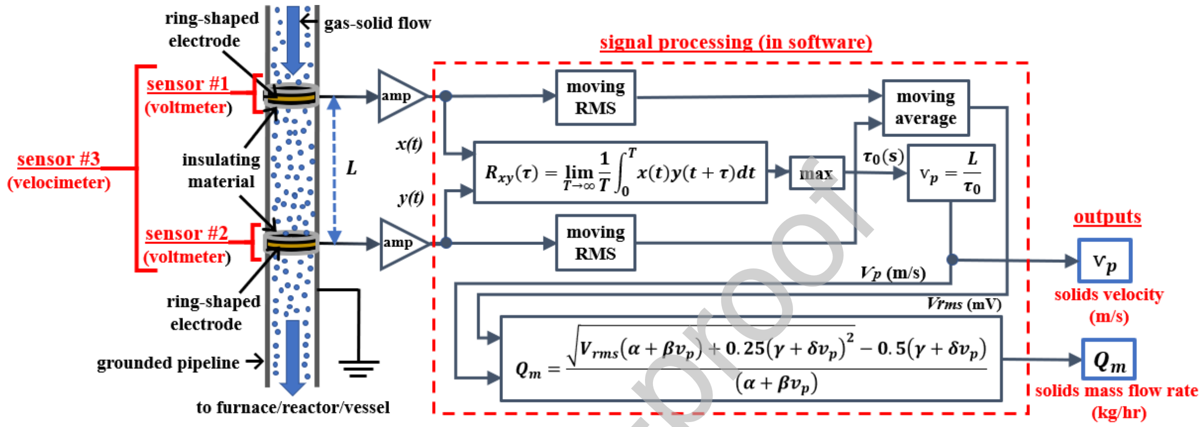


FIG. 9b - New model (eq. 15) fit with Q_m

As can be seen from figures 7, 8 and 9, the newly presented meter model of equation 15 exhibits a higher level of accuracy. Preliminary results with such a model indicate a mean relative error of a maximum relative error of less than 6.5%, which is acceptable for a multiphase meter with the additional advantage that there is no requirement to measure air-solids ratio. Whilst the error is slightly higher than that of the model of equation 3 that incorporates air-solids ratio, the error is less that of previous models of equations 3, 17 and 18 from the literature. The results also suggest that compensating the effect of velocity, simply by dividing meter voltage by measured velocity and a constant, as with equation or transposing equation 18, will not yield an accurate value for mass flow rate. Also the model of equation 18, whilst more accurate than equation 17, does not exhibit an acceptable level of accuracy as the maximum relative error is as much as 13%. However, the newly presented model of equation 15 exhibits half the maximum relative error at 6.5%, and so if transposed and utilised as a calibration function it will result in significantly higher accuracy for solids mass flow rate measurement.

8. Model Application

As the calibration function of equation 16 only requires rms voltage and particle velocity, only two (or more) electrodes are then required and the measurement system can be of the form shown in Figure



10.

FIG. 10. Simplified measurement system

As shown, only two ring-shaped electrodes are required, though more can be used to potentially increase performance. The two electrodes actually act as three sensors – two electrostatic voltage meters and an electrostatic cross-correlation velocimeter as a sensor fusion. The continuously sampled data from each sensor is used to determine mass flow rate, subsequent to signal processing incorporating mathematical functions in software - the two main functions being the cross-correlation function of equation 4 and the calibration function of equation 16. Given that measurement of solids flow velocity is necessary in order determine mass flow rate, the measured velocity can also constitute an additional output. Therefore two measured variables can be obtained using just two (or more) simple electrodes effectively acting as three (or more) sensors, and with their processed output signals utilised with the newly presented calibration function, a simple yet accurate gas-solid flow metering system is the result.

9. Conclusions

Both presented models of equations 8 and 15 exhibit a low mean relative error (less than 1%) and low maximum relative error (5% and 6.5% respectively) when compared to test data. Additionally, the calibration function of equation 16 de-necessitates determination of air-solids ratio which is difficult to measure in practice, and requires only rms voltage and particle velocity measurement. This enables the overall system to be less complex, comprised solely of two or more ring-shaped electrodes, and could even be achieved with a single meter assembly incorporating two electrodes. A method is provided for the calibration of simple yet relatively accurate non-intrusive solids mass flow measurement system, capable of utilisation in flow control loops. This could then enable process optimisation and reductions in waste and emissions for some of the most energy intensive and polluting industrial processes in global production of energy and materials. Subsequent work will ascertain both a theoretical basis for the obtained model, (i.e. a bottom-up as opposed to top-down modelling approach) and optimum filter coefficients for online input data smoothing whilst maintaining a suitably fast response to varying flow parameters, in order to maximise the dynamic performance of the measurement system.

Conflicts of interest

No conflict of interest exists in the submission of our manuscript *"A low-error calibration function for an electrostatic gas-solid flow meter obtained via machine learning techniques with experimental data"*

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